Update of electroweak parameters from Z decays

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The ALEPH Collaboration[*)]

Abstract

Based on 520,000 fermion pairs accumulated during the first three years of data collection by the ALEPH detector at LEP, updated values of the resonance parameters of the Z are determined to be $M_{\mathrm{Z}} = (91.187 \pm 0.009)$ GeV, $\Gamma_{\mathrm{Z}} = (2.501 \pm 0.012)$ GeV, $\sigma^0_{\mathrm{had}} = (41.60 \pm 0.27)$ nb, and $R_\ell = 20.78 \pm 0.13$. The corresponding number of light neutrino species is $N_\nu = 2.97 \pm 0.05$. The forward-backward asymmetry in lepton-pair decays is used to determine the ratio of vector to axial-vector couplings of leptons: $g^2_{\mathrm{V}}(M^2_{\mathrm{Z}})/g^2_{\mathrm{A}}(M^2_{\mathrm{Z}}) = 0.0052 \pm 0.0016$ combining this with ALEPH measurements of the b and c quark asymmetries and τ polarization gives $\sin^2\theta^{eff}_{\mathrm{W}} = 0.2326 \pm 0.0013$. Assuming the minimal Standard Model, and including measurements of $M_{\mathrm{W}}/M_{\mathrm{Z}}$ from $p\overline{p}$ colliders and neutrino-nucleon scattering, the mass of the top quark is $M_{\mathrm{top}} = 156 \pm^{22}_{25} \pm^{17}_{22\mathrm{Higgs}}$ GeV.

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1 Introduction

The resonance parameters of the Z boson provide both fundamental inputs to the Standard Model of electroweak interactions, and sensitive tests of the predictions of the theory. During the 1991 running of LEP, the ALEPH detector collected 12.0 pb^{-1} of integrated luminosity. These data provided approximately 330,000 fermion pairs which are used to determine the resonance parameters of the Z. The large increase in statistics over the previous ALEPH publications [1] allows a more precise determination of all these parameters.

This publication contains the analysis based on the total sample of 520,000 fermion pairs collected by ALEPH at LEP. Only the differences between the present analysis and the analysis described in previous publications will be discussed below. Details of the analysis can be found in [1].

2 Cross Section and Asymmetry Measurements

The ALEPH detector was upgraded in 1991 to include a silicon vertex detector surrounding the beampipe, and a second layer of muon detectors on the outside of the detector. The selections for hadronic and leptonic events were not changed from those in [1]. The increased material between the beampipe and the TPC results in a higher $\tau^+\tau^-$ background for the hadronic event selections, and a decreased efficiency (about 1%) for the $\tau^+\tau^-$ event selection, while the second layer of muon detectors increases the selection efficiency for $\mu^+\mu^-$ events. These changes did not modify the estimated systematic errors for the hadron and lepton selection efficiencies.

In the $\tau^+\tau^-$ selection, several components of the systematic error are limited by the statistical precision of the data sample. The additional data from 1991 were used to reevaluate these errors, resulting in a total systematic uncertainty of 0.6% for the $\tau^+\tau^-$ selection (compared to 0.9% in 1990 [1]). The systematic uncertainties for the other event selections are the same as in [1]: 0.2% for the hadronic selection, 0.4% for the e^+e^- selection, 0.5% for the $\mu^+\mu^-$ selection, and 0.4% for the flavour independent lepton selection (common lepton method).

The determination of the absolute luminosity is described in detail in reference [2]. The systematic error on the determination of the absolute luminosity was reevaluated using a new Monte Carlo program BHLUMI [3]. BHLUMI is a multi-photon $\mathcal{O}(\alpha)$ generator with exclusive exponentiation. In addition, events were simulated with the first-order generator BABAMC [4], used previously [2] corrected with the higher order generator LUMLOG [5]. The absolute cross sections derived from the two generators are the same (within one sigma statistically), however, BHLUMI more closely reproduces the data in terms of the energy distributions. For this reason, BHLUMI is used to measure the cross section and to evaluate the systematic errors. The contribution of terms containing Z exchange was calculated using BABAMC. The total theoretical error on the absolute luminosity is estimated to be below 0.3% [6]

Figure 1 shows the total energy distribution for data and the BHLUMI simulation where all selection requirements other than total energy requirement have been applied to the data. As a result of the better agreement of BHLUMI and the data, the uncertainties due to the energy and $\Delta\phi$ requirements are slightly reduced with respect to 1990. The

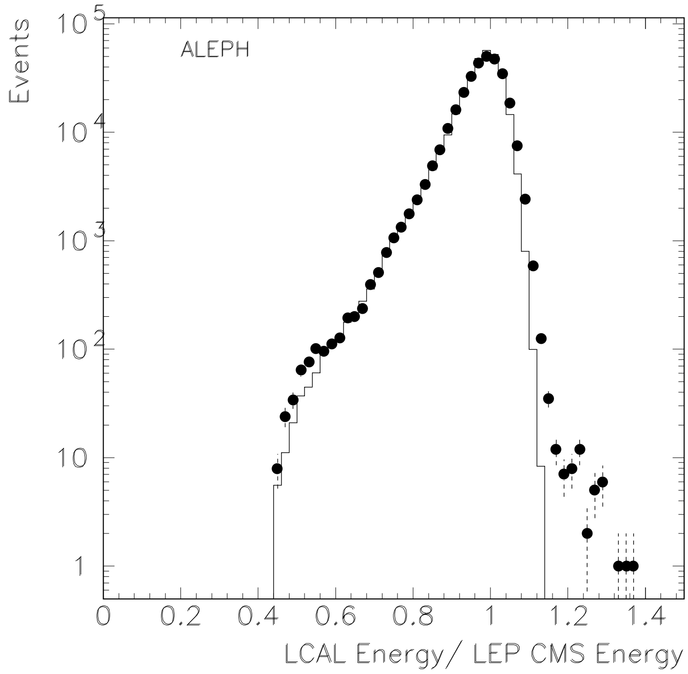

Figure 1: Sum of energy in the fiducial and non-fiducial sides of the luminosity calorimeter normalized to the center-of-mass energy. The data are shown as solid points and the BHLUMI simulation is shown as a histogram.

dominant error resulting from the fiducial boundary definition has also been reduced to 0.32%. Adding the systematic errors in quadrature results in an overall experimental uncertainty of 0.45% compared to the systematic uncertainty of 0.6% previously cited [2]. Combining the theoretical and experimental uncertainties results in a total uncertainty on the absolute luminosity of 0.55%.

In order to reduce the statistical error on the relative luminosity at different energies, a Bhabha selection with a larger acceptance is used. This selection is an extension of the method used to determine the absolute luminosity described in ref [2]. In the standard selection, it is required that one of the Bhabha candidates lies within a tight fiducial region and the other candidate lies within a loose fiducial region of the detector. In the higher statistics method, this requirement is relaxed by only demanding that one Bhabha candidate lies within the loose fiducial region, while the other candidate is not required to be in any fiducial region. The cross section for these events is approximately 1.5 times as large as for events used in the absolute luminosity determination. The overall luminosity from this larger acceptance sample is scaled to the absolute luminosity measurement described above. Even though the limited knowledge of the geometry and material at the inner edge of the detector compromises the determination of an absolute luminosity in the higher statistics method, these uncertainties are independent of the center of mass energy, so that the rescaled values may be used for the relative luminosity. The statistical

$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ ($\rm nb^{-1}$)	$\sigma_{\rm had}$ (nb)	σ_{ee} (nb)	$\sigma_{\mu\mu}$ (nb)	$\sigma_{\tau\tau}$ (nb)	$\sigma_{\ell\ell}$ (nb)
88.223	480.2 ± 3.4	4.61 ± 0.10		0.242 ± 0.025	0.171 ± 0.024	
89.217	520.3 ± 3.6	8.41 ± 0.14		0.497 ± 0.034	0.385 ± 0.034	
90.217	444.0 ± 3.4	18.59 ± 0.25	0.924 ± 0.063	0.902 ± 0.049	0.886 ± 0.054	2.753 ± 0.104
91.215	3504.6 ± 9.6	30.46 ± 0.12	1.482 ± 0.026	1.426 ± 0.022	1.491 ± 0.024	4.407 ± 0.044
92.207	553.8 ± 3.8	21.83 ± 0.25	1.092 ± 0.055	1.001 ± 0.047	1.061 ± 0.053	3.137 ± 0.091
93.209	594.2 ± 4.0	12.48 ± 0.17		0.633 ± 0.036	0.553 ± 0.037	
94.202	641.6 ± 4.2	7.99 ± 0.12		0.432 ± 0.029	0.408 ± 0.031	
88.464	671.0 ± 4.0	5.47 ± 0.10		0.256 ± 0.022	0.268 ± 0.026	
89.455	798.9 ± 4.4	10.01 ± 0.13		0.536 ± 0.029	0.505 ± 0.031	
90.212	748.5 ± 4.3	18.23 ± 0.19	0.896 ± 0.048	0.920 ± 0.039	0.939 ± 0.043	2.741 ± 0.080
91.207	2939.3 ± 8.8	30.59 ± 0.14	1.544 ± 0.029	1.536 ± 0.025	1.475 ± 0.027	4.440 ± 0.039
91.238	4608.4 ± 11.0	30.63 ± 0.11	1.463 ± 0.023	1.475 ± 0.020	1.485 ± 0.022	4.595 ± 0.050
91.952	694.3 ± 4.3	25.31 ± 0.25	1.206 ± 0.051	1.207 ± 0.047	1.299 ± 0.052	3.708 ± 0.090
92.952	680.0 ± 4.3	14.59 ± 0.17		0.660 ± 0.035	0.707 ± 0.039	
93.701	765.0 ± 4.6	10.20 ± 0.13		0.512 ± 0.029	0.506 ± 0.031	

Table 1: Hadron and Lepton Cross Sections for the 1990 (top) and 1991 (bottom) data. Only statistical errors are given, and points not used in the fits are omitted. The 1991 data at 91.2 GeV are separated for running before (91.238 GeV) and after (91.207 GeV) the LEP energy scan. The 1989 data remain as published in [1].

uncertainty in the normalization of the absolute and relative luminosity measurements is added in quadrature with the systematic error on the absolute luminosity determination leading to an overall error of 0.56% on the relative luminosity determination. Relative luminosities were calculated for the 1990 and 1991 data.

The measured cross sections for the hadron and lepton selections are shown in Table 1. Because of the use of the relative luminosity for the 1990 data, as well as an improved estimate of the LEP machine energies for the 1990 period [7], new values are given for the 1990 cross sections superseding the previous ALEPH cross sections [1]. For both the 1990 and 1991 data, the cross sections are for events for which the invariant mass of the Z decay products after initial-state radiation ($\sqrt{s'}$) is greater than 10% of the centre-of-mass energy. For lepton events, this is changed from [1] where the cross sections correspond to events with $\sqrt{s'}$ greater than twice the lepton mass. These cross sections also contain a correction for the 51 ± 5 MeV spread in the LEP center-of-mass energy. In this table only the statistical errors (including the statistical error for the luminosity measurement) are included. The hadronic cross section data are plotted in Figure 2.

The forward-backward asymmetry in the lepton pair data is obtained by performing a fit to the lepton angular distribution with the function [8]

$$\frac{d\sigma}{d\cos\theta^*} = C(1 + \cos^2\theta^* + \frac{8}{3}A_{\rm FB}\cos\theta^*)F(\cos\theta^*), \tag{1}$$

where $F(\cos\theta^*)$ corrects for the t-channel contribution in the e^+e^- distribution, and is unity for the other lepton angular distributions. Plots of the asymmetries as a function of centre-of-mass energy are shown in Figure 3, and given numerically in Table 2.

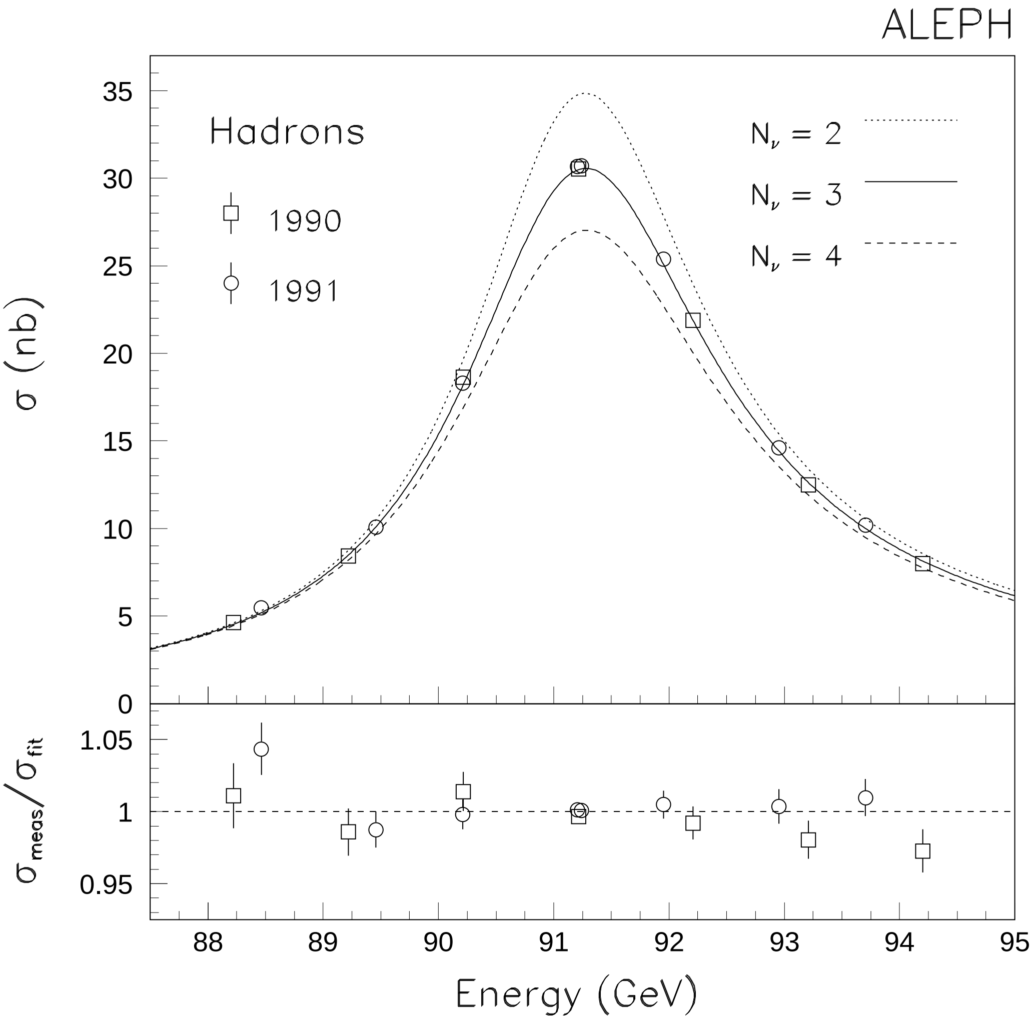

Figure 2: Cross sections for $e^+e^- \to$ hadrons as functions of the centre-of-mass energy for the 1990 and 1991 data. The Standard Model predictions for N_ν = 2,3, and 4 are shown. The lower plot shows the ratio of the measured points to the best fit values.

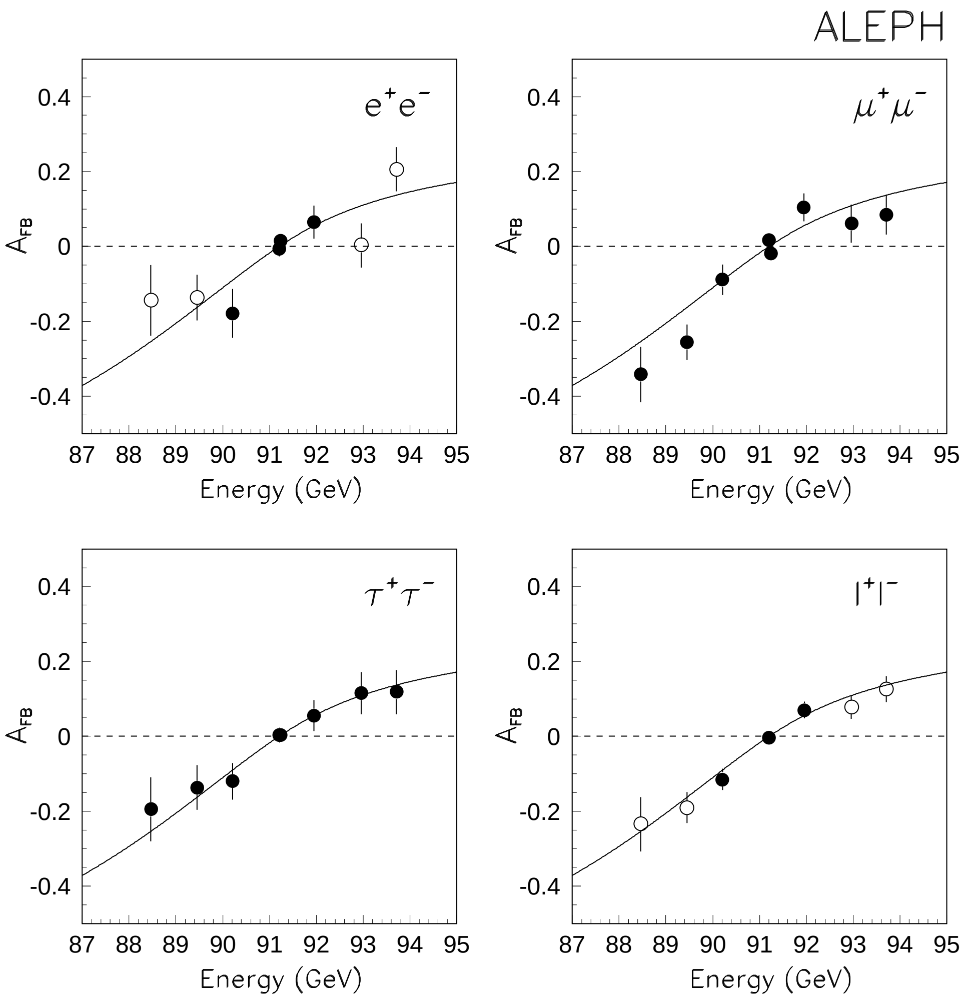

Figure 3: Forward-backward asymmetry for e^-, μ^-, τ^-, and l^- in lepton-pair events as a function of the centre-of-mass energy. The lines are the results of the fit of section 5 assuming lepton universality. Points with open circles are not used in the fit. Only 1991 data are shown.

$\sqrt{s}(GeV)$	$A_{\mathrm{FB}}^{e^+e^-}$	$A_{\mathrm{FB}}^{\mu^+\mu^-}$	$A_{\mathrm{FB}}^{\tau^+\tau^-}$
88.464		-0.342 ± 0.074	-0.195 ± 0.085
89.455		-0.256 ± 0.048	-0.137 ± 0.060
90.212	-0.179 ± 0.065	-0.089 ± 0.040	-0.120 ± 0.049
91.207	-0.006 ± 0.020	$+0.016 \pm 0.016$	$+0.003 \pm 0.019$
91.238	$+0.014 \pm 0.017$	-0.018 ± 0.013	$+0.003 \pm 0.015$
91.952	$+0.065 \pm 0.044$	$+0.104 \pm 0.037$	$+0.055 \pm 0.041$
92.952		$+0.061 \pm 0.051$	$+0.115 \pm 0.056$
93.701		$+0.085 \pm 0.053$	$+0.118 \pm 0.059$

Table 2: Forward-backward asymmetries for Z $\rightarrow$ lepton pairs as a function of the centre-of-mass energy. Only statistical errors are shown, and points not used in the fits are omitted. The data for 1989 and 1990 remain as published in [1].

3 Results for Lineshape Parameters

The definitions of the lineshape parameters used here are those of ref [9]. In order to extract the parameters from the observed cross sections for hadrons and leptons, a model-independent description of the lineshape is used [10, 11, 12, 13]. The computer program `MIZA` [14] is used to fit the cross sections. The fitting program was modified this year to include the effect of initial state pair creation [15]. This correction results in a 0.3% increase in the fitted peak cross section, a 2.4 MeV decrease in the total width, and a 1.5 MeV decrease in the Z mass.

The LEP energy errors were introduced into the fitting procedure taking into account the correlations in the energy measurement errors among scan points, and between the 1990 and 1991 data.

3.1 Four Parameter fit

Two fits to the cross section data are used to determine the resonance parameters. In the first, the hadronic, $\mu^+\mu^-$, and $\tau^+\tau^-$cross sections are used at all energy scan points, while the e^+e^- cross section data are only used for scan points where $|\sqrt{s} - M_{\mathrm{Z}}| < 1.5$ GeV in order to reduce the uncertainty resulting from t-channel subtraction. As a check, the fits are repeated using the hadronic cross sections at all points, and the common lepton sample for points with $|\sqrt{s} - M_{\mathrm{Z}}| < 1.5$ GeV. In both fits, a χ^2 minimization is performed assuming lepton universality, and including all systematic errors. In this case, four resonance parameters are extracted: the Z mass M_{Z}, the total width Γ_{Z}, the peak hadronic cross section σ^0_{had}, and the ratio of hadron to lepton partial widths $R_\ell \equiv \Gamma_{\mathrm{had}}/\Gamma_\ell$.

The results of the fits for the combined 1989, 1990, and 1991 data are shown in Table 3. The correlation matrix for the fit is found in the appendix. The parameter R_ℓ is the most sensitive for evaluating the difference between the results for the common lepton and individual lepton data. The common lepton data result in a value of $R_\ell = 20.69 \pm 0.13$ which can be compared to the value from the individual lepton data $R_\ell = 20.78 \pm 0.13$. The difference between the two measurements is $\Delta R_\ell = 0.09 \pm 0.07$ where the correlation between the event samples has been taken into account. The two methods give consistent values for the fit parameters. In the following only the results of the fits to the individual

Parameter	1989-1991 Data
M_Z [GeV]	91.187 ± 0.009
Γ_Z [GeV]	2.501 ± 0.012
σ^0_{had} [nb]	41.60 ± 0.27
R_ℓ	20.78 ± 0.13
Γ_ℓ [MeV]	84.22 ± 0.48
Γ_{had} [MeV]	1751 ± 11
Γ_{inv} [MeV]	498 ± 9
Br(Z $\rightarrow$ hadrons) [%]	69.99 ± 0.34
Br(Z $\rightarrow \ell^+\ell^-$) [%]	3.367 ± 0.014
χ^2	79/81 DF

Table 3: Results of the fit to the cross sections assuming lepton universality. The errors shown include systematic and statistical uncertainties.

lepton data will be presented.

From the fit parameters, it is possible to derive additional parameters: the partial widths for leptons (Γ_ℓ) and hadrons (Γ_{had}), the branching ratios for leptons and hadrons, and the invisible width defined as $\Gamma_{\mathrm{inv}} = \Gamma_Z - \Gamma_{\mathrm{had}} - 3\Gamma_\ell$. The results for these parameters are also shown in Table 3. From the measured value of $\Gamma_{\mathrm{inv}}/\Gamma_\ell = 5.91 \pm 0.11$, and using the value of Γ_ℓ/Γ_ν obtained from the electroweak theory as in [1] and equal to 0.5016 ± 0.0007 one obtains the following result for the number of light neutrino species

$$N_\nu = 2.97 \pm 0.05$$

where it is assumed $\Gamma_{\mathrm{inv}} = N_\nu \Gamma_\nu$.

Within the minimal Standard Model, the parameters R_ℓ, and σ^0_{had} have little dependence on M_{top} or M_{Higgs}, and hence their values test the predictions without uncertainty from the unknown masses. Figure 4 shows the probability contours for the two parameters given by the fit along with the Standard Model prediction for 3 light neutrino generations. The main uncertainty in the prediction shown for the Standard Model arises from the uncertainty on the strong coupling constant α_s. The dependence of R on α_s, using the third-order expansion in α_s in the $\overline{\mathrm{MS}}$ scheme, is [16]

$$R_\ell = R^\circ(1 + 1.05\frac{\alpha_s}{\pi} + (0.9 \pm 0.1)(\frac{\alpha_s}{\pi})^2 - 13(\frac{\alpha_s}{\pi})^3),$$

where $R^\circ = 19.98 \pm 0.03$ is the Standard Model value for R_ℓ which is predicted when there are no final state strong interactions. The measured value of $R_\ell = 20.78 \pm 0.13$ gives the following value for the strong coupling constant:

$$\alpha_s(M_Z^2) = 0.118 \pm 0.018.$$

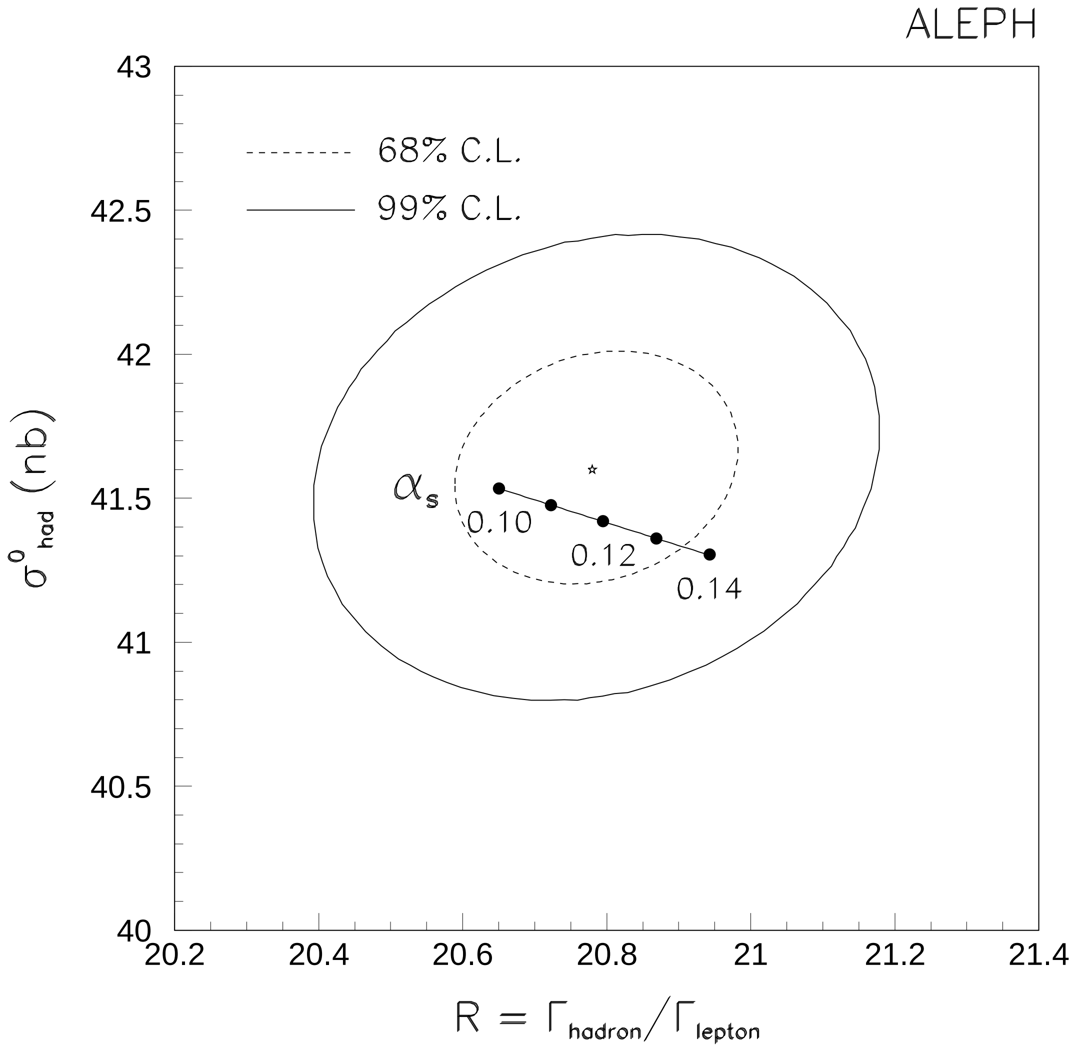

Figure 4: Contours of constant χ^2 for the hadronic peak cross section $\sigma^0_{\rm had}$ as a function of $\Gamma_{\rm had}/\Gamma_\ell$ together with the Standard Model prediction as a function of the QCD coupling constant $\alpha_{\rm s}$.

Parameter	1989-1991 Data
M_Z [GeV]	91.187 ± 0.009
Γ_Z [GeV]	2.501 ± 0.012
$\sigma^0_{\rm had}$ $[nb]$	41.60 ± 0.27
R_e	20.69 ± 0.21
R_μ	20.88 ± 0.20
R_τ	20.77 ± 0.23
Γ_e [MeV]	84.43 ± 0.60
Γ_μ [MeV]	83.66 ± 0.95
Γ_τ [MeV]	84.09 ± 1.10
$\mathrm{Br}(\mathrm{Z} \to e^+e^-)$ [%]	3.375 ± 0.019
$\mathrm{Br}(\mathrm{Z} \to \mu^+\mu^-)$ [%]	3.345 ± 0.036
$\mathrm{Br}(\mathrm{Z} \to \tau^+\tau^-)$ [%]	3.362 ± 0.041
σ^0_e $[nb]$	2.011 ± 0.023
σ^0_μ $[nb]$	1.993 ± 0.021
σ^0_τ $[nb]$	2.003 ± 0.025
χ^2	78/79 DF

Table 4: Results of the fit to the cross sections without assuming lepton universality. The errors shown include systematic and statistical uncertainties.

3.2 Six Parameter fit

Without the assumption of lepton universality, a fit to the individual lepton data yields six parameters, M_Z , Γ_Z , $\sigma^0_{\rm had}$, and R_e, R_μ, R_τ, the ratio of the hadronic partial width to the partial widths for each individual lepton species.

The results of the six parameter fit to the 1989-1991 data sample are shown in Table 4. The agreement between R_e, R_μ, R_τ provides a test of lepton universality at the level of 2%. Also shown in the table are the values for the partial widths, branching ratios, and peak cross sections for the individual lepton species which are derived from the fit parameters.

4 Systematic Errors

The systematic errors which are included in the above results come from three main sources:

- the uncertainty in the LEP energy measurement,
- the systematic errors in the efficiencies of the hadronic and leptonic selections,
- the systematic error in the luminosity measurement of 0.56%.

The LEP energy error has four components: an absolute error, an error in reproducibility of the energy setting, an uncertainty in the relative energy scale, and an un-

		Statistical	Systematic Errors		
Parameter	Value	Error	LEP	Selection	Luminosity
M_Z [GeV]	91.187 ± 0.009	0.006	0.007	-	-
Γ_Z [GeV]	2.501 ± 0.012	0.011	0.004	0.002	-
σ^0_{had} [nb]	41.60 ± 0.27	0.10	-	0.08	0.23
R_ℓ	20.78 ± 0.13	0.11	-	0.07	-
Γ_ℓ [MeV]	84.22 ± 0.48	0.37	0.14	0.14	0.24
Γ_{had} [MeV]	1751 ± 11	8	3	5	5
Γ_{inv} [MeV]	498 ± 9	6	1	4	5
N_ν	2.97 ± 0.05	0.03	-	0.02	0.04

Table 5: Statistical and systematic errors on the resonance parameters for the combined 1989-1991 data.

correlated point-to-point energy uncertainty. The first two of these errors have been reduced for data taken during the 1991 energy scan by the measurement of the absolute energy using resonant spin depolarization at 92 GeV [17]. The absolute center-of-mass energy for this period is known to $\pm 5.7 \times 10^{-5}$ with a reproducibility of 1×10^{-4}. For 1991 data taken before the energy scan, the error on the absolute center-of-mass energy is $\pm 20 \times 10^{-5}$, and for 1990 data the error is now estimated to be $\pm 29 \times 10^{-5}$ [7]. This error contributes directly to the measurement of M_Z but not to the width measurements. Uncertainty in the non-linearity of the LEP dipole magnets results in an uncertainty of 3.7 MeV on the measurement of Γ_Z, and 2.6 MeV on the measurement of M_Z. As a check of these estimates, M_Z was measured separately for 1990 and 1991. The 1990 data give $M_Z = 91.175 \pm 0.010_{stat} \pm 0.027_{LEP}$ while for 1991 $M_Z = 91.190 \pm 0.007_{stat} \pm 0.007_{LEP}$ which are consistent.

Table 5 shows the contribution of the systematic errors coming from the LEP energy uncertainty, the luminosity uncertainty, and the combined uncertainties of the hadronic and individual leptonic selections. Only the hadronic peak cross section, the number of neutrino species, and M_Z are systematically limited with the current data sample.

5 Fits to Lepton Asymmetries

The forward-backward asymmetries of the lepton channels as a funtion of center-of-mass energy are used to determine the effective coupling constants $g_{\mathrm{V}}(M_Z^2)$ and $g_{\mathrm{A}}(M_Z^2)$. The data are fit to the formulae given in ref. [1] which include corrections for: QED initial and final state radiation, interference between initial and final state radiation, running QED coupling constant, and the imaginary part of the photon propagator [18, 19, 20]. The QED corrected asymmetry at the Z peak, A^0_{FB} is given by

$$A^0_{\mathrm{FB}} = \frac{3}{4}\frac{2g_{\mathrm{Ve}}g_{\mathrm{Ae}}}{g^2_{\mathrm{Ve}} + g^2_{\mathrm{Ae}}}\frac{2g_{\mathrm{V}\ell}g_{\mathrm{A}\ell}}{g^2_{\mathrm{V}\ell} + g^2_{\mathrm{A}\ell}}. \qquad (2)$$

The variation of the asymmetry away from the Z peak depends mainly on $g_{\mathrm{Ae}}g_{\mathrm{A}\ell}$ and removes the ambiguity in magnitude between $g_{\mathrm{V}\ell}$ and $g_{\mathrm{A}\ell}$ as does the QED-corrected

	No P_τ constraint			With P_τ constraint	
	$A^0_{\rm FB}$	$g_{\rm V}(M_{\rm Z}^2)$	$g_{\rm A}(M_{\rm Z}^2)$	$g_{\rm V}(M_{\rm Z}^2)$	$g_{\rm A}(M_{\rm Z}^2)$
e	0.0140 ± 0.0093	$-0.034^{+0.015}_{-0.010}$	$-0.503^{+0.002}_{-0.002}$	$-0.034^{+0.006}_{-0.005}$	-0.5029 ± 0.0018
μ	0.0074 ± 0.0072	$-0.018^{+0.018}_{-0.024}$	$-0.501^{+0.003}_{-0.003}$	$-0.019^{+0.018}_{-0.019}$	-0.5014 ± 0.0029
τ	0.0269 ± 0.0082	$-0.067^{+0.024}_{-0.054}$	$-0.499^{+0.010}_{-0.004}$	$-0.039^{+0.006}_{-0.006}$	-0.5016 ± 0.0033
ℓ	0.0154 ± 0.0048	$-0.036^{+0.006}_{-0.005}$	-0.5021 ± 0.0015	$-0.034^{+0.004}_{-0.003}$	-0.5022 ± 0.0015

Table 6: Peak asymmetries and effective vector and axial-vector coupling constants for e, μ, and τ separately, and assuming lepton universality. Also given are the same results using the added constraint of τ polarization.

partial width for leptons

$$\Gamma_\ell = \frac{G_F M_{\rm Z}^3}{6\sqrt{2}\pi}(g_{{\rm V}\ell}^2 + g_{{\rm A}\ell}^2)(1 + \frac{3}{4}\frac{\alpha}{\pi}). \qquad (3)$$

The fit to the 1989-1991 data assumes lepton universality, and uses the resonance parameters from the four-parameter fit to the individual lepton data as a constraint. In the e^+e^- channel, only the points with $|\sqrt{s} - M_{\rm Z}| < 1.5$ GeV are used in the fit. The peak asymmetry and coupling constants are determined to be

$$A^0_{\rm FB} = 0.0154 \pm 0.0048,$$

$$g_{\rm V}^2(M_{\rm Z}^2)/g_{\rm A}^2(M_{\rm Z}^2) = 0.0052 \pm 0.0016,$$

$$g_{\rm V}(M_{\rm Z}^2) = -0.036^{+0.006}_{-0.005}, \quad \text{and} \quad g_{\rm A}(M_{\rm Z}^2) = -0.5021 \pm 0.0015$$

where the value of $g_{\rm A}(M_{\rm Z}^2)$ is determined mainly by the value of Γ_ℓ used as a constraint in the fit. The correlation between $A^0_{\rm FB}$ and the resonance parameters is 0.07 for the mass, and less than 0.01 for the other parameters.

The fits are repeated without assuming lepton universality, using the results of the six-parameter fit. In this case, couplings are extracted for each of the individual lepton species. Improved results for the couplings are obtained by using the ALEPH measurements of the couplings of the τ and electron from τ polarization [21] as constraints. The results are summarized in Table 6 and plotted in figure 5, which shows the observed probability contours for the coupling constants along with the Standard Model predictions for the couplings. The results are in agreement with lepton universality.

6 Effective Weak Mixing Angle

The Standard Model predictions for the asymmetries can be written in terms of the effective electroweak mixing angle $\sin^2\theta_{\rm W}^{eff}$. The effective vector and axial-vector couplings are extracted from the forward-backward asymmetries using equation (2). The couplings are written in terms of $\sin^2\theta_{\rm W}^{eff}$ as

$$\frac{g_{\rm V}(M_{\rm Z}^2)}{g_{\rm A}(M_{\rm Z}^2)} = (1 - 4\sin^2\theta_{\rm W}^{eff}). \qquad (4)$$

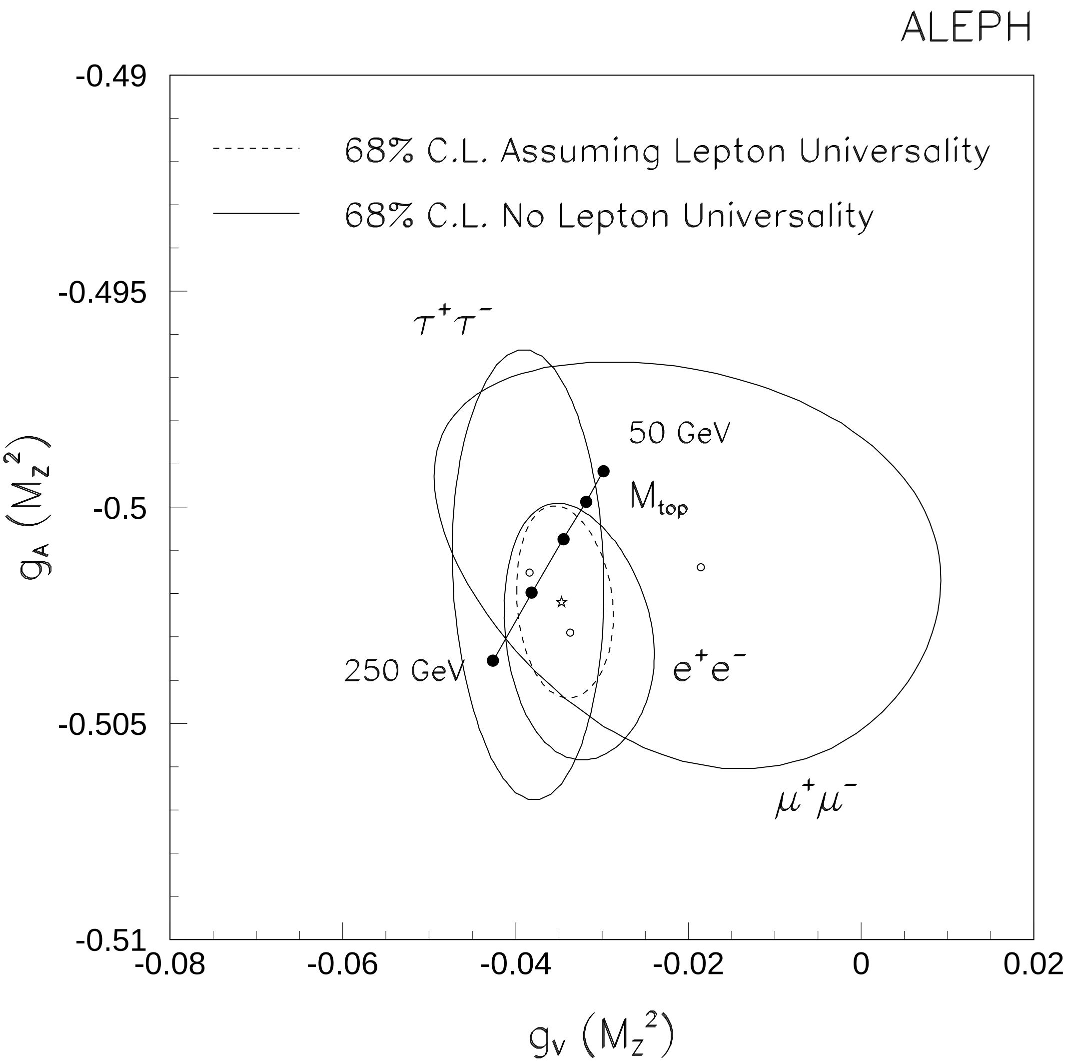

Figure 5: Probability contours for $g_{\rm V}(M_{\rm Z}^2)$ and $g_{\rm A}(M_{\rm Z}^2)$ for each lepton species from leptonic forward-backward asymmetries and τ polarization. Also shown is the result assuming lepton universality. The points are the expectations of the Standard Model for top masses from 50 to 250 GeV, assuming $\alpha_s = 0.125 \pm 0.005$ and $M_{\rm Higgs} = 300$ GeV. The error elipses ignore the correlations between the $g_{\rm V}(M_{\rm Z}^2)$ of each species.

Measurement	Measured quantity	value	$\sin^2\theta_W^{eff}$
Lepton F-B asymmetry	$g_V^2(M_Z^2)/g_A^2(M_Z^2)$	0.0052 ± 0.0016	0.2320 ± 0.0028
Quark charge asymmetry	$< Q_{FB} >$	-0.0084 ± 0.0016	0.2307 ± 0.0052
Tau polarization	$\mathcal{A}_\tau$	0.143 ± 0.023	0.2320 ± 0.0029
Tau pol. F-B asymmetry	$\mathcal{A}_e$	0.120 ± 0.026	0.2350 ± 0.0033
$b\bar{b}$ asymmetry	$A_{FB}^0(b)$	0.090 ± 0.013	0.2340 ± 0.0023
$c\bar{c}$ asymmetry	$A_{FB}^0(c)$	0.100 ± 0.024	0.2257 ± 0.0053
Asymmetry average			0.2326 ± 0.0013

Table 7: Summary of ALEPH measurements of $\sin^2\theta_W^{eff}$ from asymmetries. The $c\bar{c}$ and $b\bar{b}$ asymmetries have been combined using a 15% correlation.

This equation defines $\sin^2\theta_W^{eff}$ such that it includes all deviations from the tree-level couplings (except for initial and final state photon radiation which are included in the fitting procedure [1]). This definition which is the preferred definition of ref [9] causes the value of $\sin^2\theta_W^{eff}$ to differ from $\sin^2\theta_W(M_Z^2)$ of [1] by +0.0007. The definition of $\sin^2\theta_W^{eff}$ is in principle flavour dependent due to an electroweak vertex correction, but the flavour dependent correction is small and is ignored here. Using this definition, the values of the couplings from the fits to the lepton asymmetries give

$$\sin^2\theta_W^{eff} = 0.2320 \pm 0.0028.$$

It is possible to improve the ALEPH measurement of $\sin^2\theta_W^{eff}$ from asymmetries by including the results of the ALEPH analysis of the quark charge asymmetry [22], the tau polarization [21], and the $b\bar{b}$ and $c\bar{c}$ forward-backward asymmetries [23]. These results are shown in Table 7. When the asymmetry values of $\sin^2\theta_W^{eff}$ are combined, the result is

$$\sin^2\theta_W^{eff} = 0.2326 \pm 0.0013.$$

The Standard Model predictions for $\sin^2\theta_W^{eff}$ and Γ_ℓ have different dependencies on the unknown Higgs and top masses which enter through radiative corrections. Comparing the values obtained from the lineshape fits for Γ_ℓ and from the asymmetries for $\sin^2\theta_W^{eff}$ provides a sensitive test of the Standard Model predictions. Figure 6 shows the probability contours comparing $\sin^2\theta_W^{eff}$ from the asymmetry measurements with Γ_ℓ. The Standard Model prediction is in agreement with the data, and these data can be used to rule out certain models, for example, the prediction for one generation of technicolor [24] is shown in Figure 6 and is excluded at the 90% confidence level.

7 Limits on the Mass of the Top Quark

The Standard Model with three neutrino species requires as input the masses of the fermions, the W and Z bosons and the Higgs boson, and the coupling constants for QED and QCD (α and α_s). Since the mass of the W is not precisely known, the model can be reparameterized to use the precisely measured G_F as input in place of M_W. Any

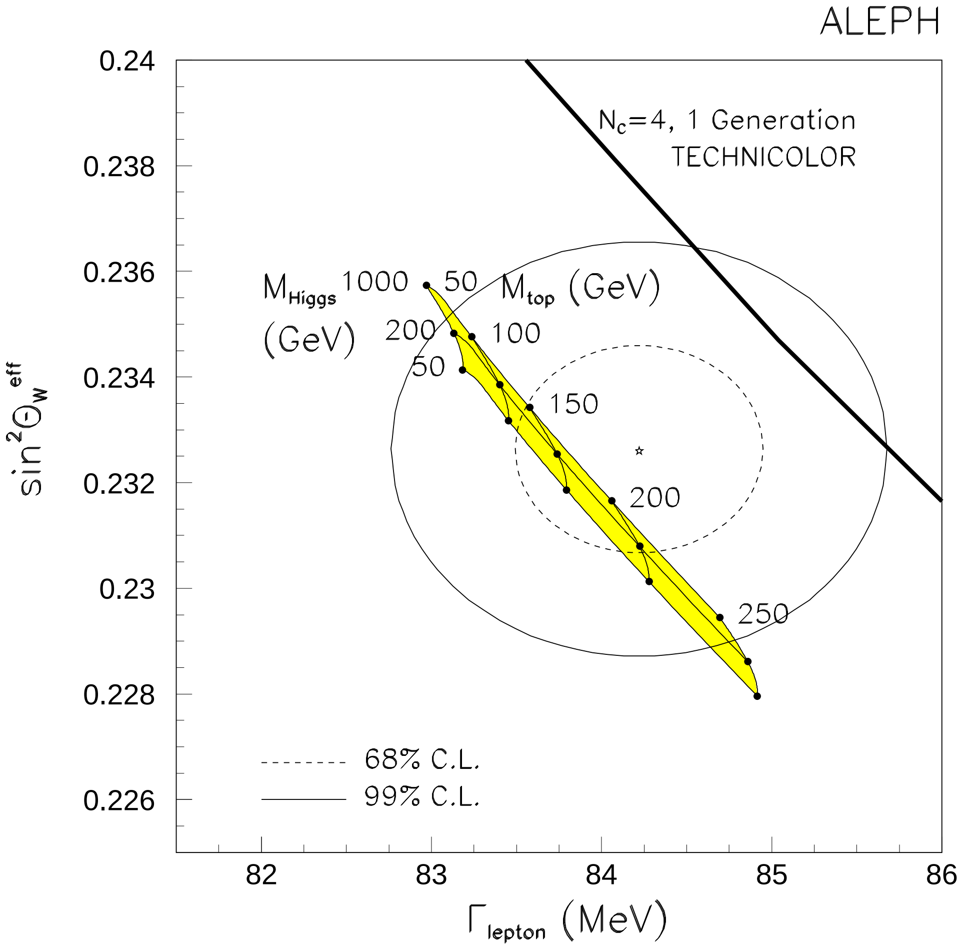

Figure 6: Contours of constant χ^2 for $\sin^2\theta_{\mathrm{W}}^{eff}$ from asymmetry measurements versus Γ_ℓ. The Standard Model predictions as a function of M_{top} and M_{Higgs} are shown. The expectation for one generation of technifermions in $N_c = 4$ technicolor is indicated also.

observable (including $\sin^2\theta_{\mathrm{W}}^{eff}$) can then be predicted in terms of these input parameters, the uncertainty of the prediction being determined by the three parameters which are the least well known (M_{top}, M_{Higgs}, and α_s).

One can then fit the observed lineshape and asymmetries to obtain best values of these unknown parameters. The Standard Model dependence on M_{Higgs} is logarithmic and small. For this reason, the value for M_{Higgs} is set to 300 GeV in the fits, and allowed to vary from 50 GeV to 1000 GeV in order to determine the uncertainty in the fit parameters coming from the unknown M_{Higgs}.

Fitting the ALEPH lineshape results: $M_{\mathrm{Z}} = (91.187 \pm 0.009)$ GeV, $\Gamma_{\mathrm{Z}} = (2.501 \pm 0.012)$ GeV, $R_\ell = 20.78 \pm 0.13$, $\sigma^0_{\mathrm{had}} = (41.60 \pm 0.27)$ nb, and the average value of $\sin^2\theta_{\mathrm{W}}^{eff}$ obtained from the asymmetry measurements $\sin^2\theta_{\mathrm{W}}^{eff} = 0.2326 \pm 0.0013$, while constraining $\alpha_s = 0.125 \pm 0.005$, the value determined in the ALEPH analysis of hadronic event shapes [25], gives

$$M_{\mathrm{top}} = (174 \pm^{27}_{32} \pm^{17}_{22\mathrm{Higgs}})\ \mathrm{GeV}$$

with χ^2=0.8 for 3 degrees of freedom. The fit also yields a prediction for M_{W} and improves the measurement of $\sin^2\theta_{\mathrm{W}}^{eff}$

$$M_{\mathrm{W}} = (80.33 \pm 0.20 \pm 0.03_{\mathrm{Higgs}})\ \mathrm{GeV},$$

$$\sin^2\theta_{\mathrm{W}}^{eff} = 0.2313 \pm 0.0010.$$

By combining the ALEPH results with measurements of M_{W} (the determination of the mass ratio $M_{\mathrm{W}}/M_{\mathrm{Z}}$ in neutrino-nucleon scattering experiments [26] and the direct measurement of M_{W} in $p\overline{p}$ colliders [27, 28]), one can fit for both M_{top} and α_s simultaneously yielding

$$\alpha_s = 0.129 \pm 0.015 \pm 0.002_{\mathrm{Higgs}}$$

$$M_{\mathrm{top}} = (156 \pm^{23}_{26} \pm^{17}_{21\mathrm{Higgs}})\ \mathrm{GeV}$$

with χ^2=2.2 for 5 degrees of freedom. The χ^2 contour for this fit is shown in Figure 7. Finally, by constraining $\alpha_s = 0.125 \pm 0.005$ and using the other measurements of M_{W} one finds

$$M_{\mathrm{top}} = (156 \pm^{22}_{25} \pm^{17}_{22\mathrm{Higgs}})\ \mathrm{GeV}.$$

The best values of M_{W} and $\sin^2\theta_{\mathrm{W}}^{eff}$ from this fit are

$$M_{\mathrm{W}} = (80.22 \pm 0.15 \pm 0.02_{\mathrm{Higgs}})\ \mathrm{GeV},$$

$$\sin^2\theta_{\mathrm{W}}^{eff} = 0.2318 \pm 0.00075 \pm 0.0002_{\mathrm{Higgs}}.$$

The inputs used in these fits can be shown graphically by expressing each observable in terms of $\sin^2\theta_{\mathrm{W}}^{eff}$ and M_{top}. The observables used in the fit are shown in figure 8 where the width of the bands represents the experimental error for each of the observables.

The results presented here are consistent with those of previous measurements [1, 29] and no discrepancies are found with the Standard Model.

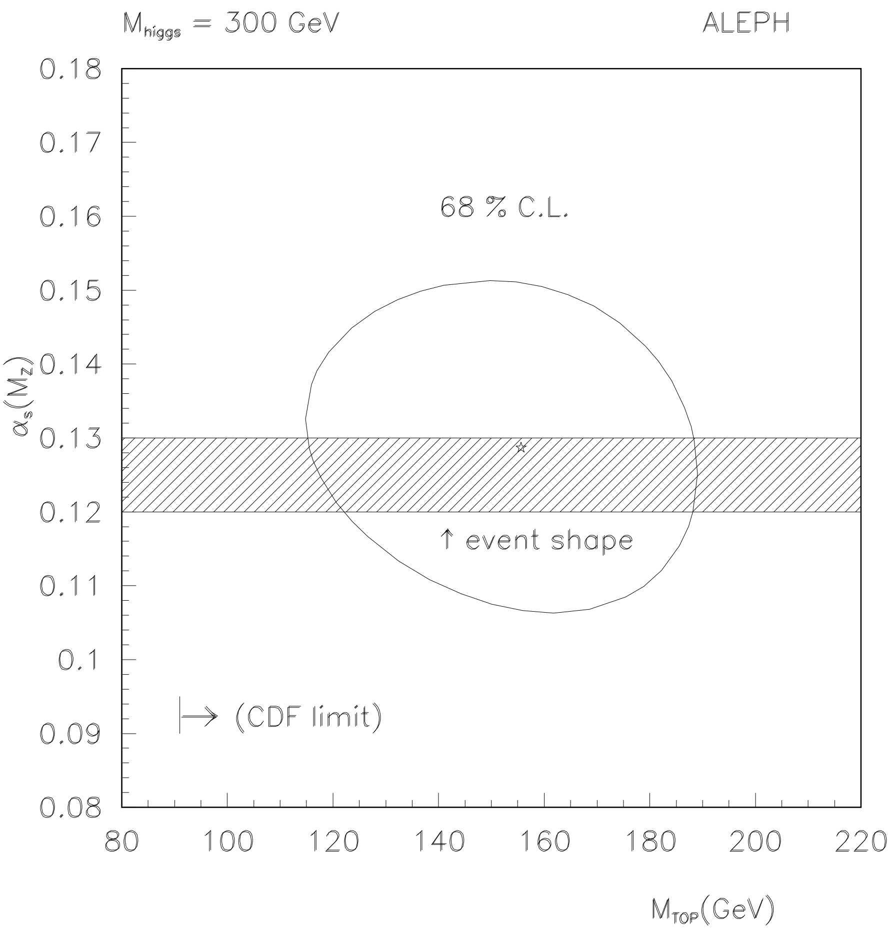

Figure 7: Contour of constant χ^2 for the fit to $M_{\rm top}$ and α_s. Also shown is the ALEPH measurement of α_s from hadronic event shape distributions.

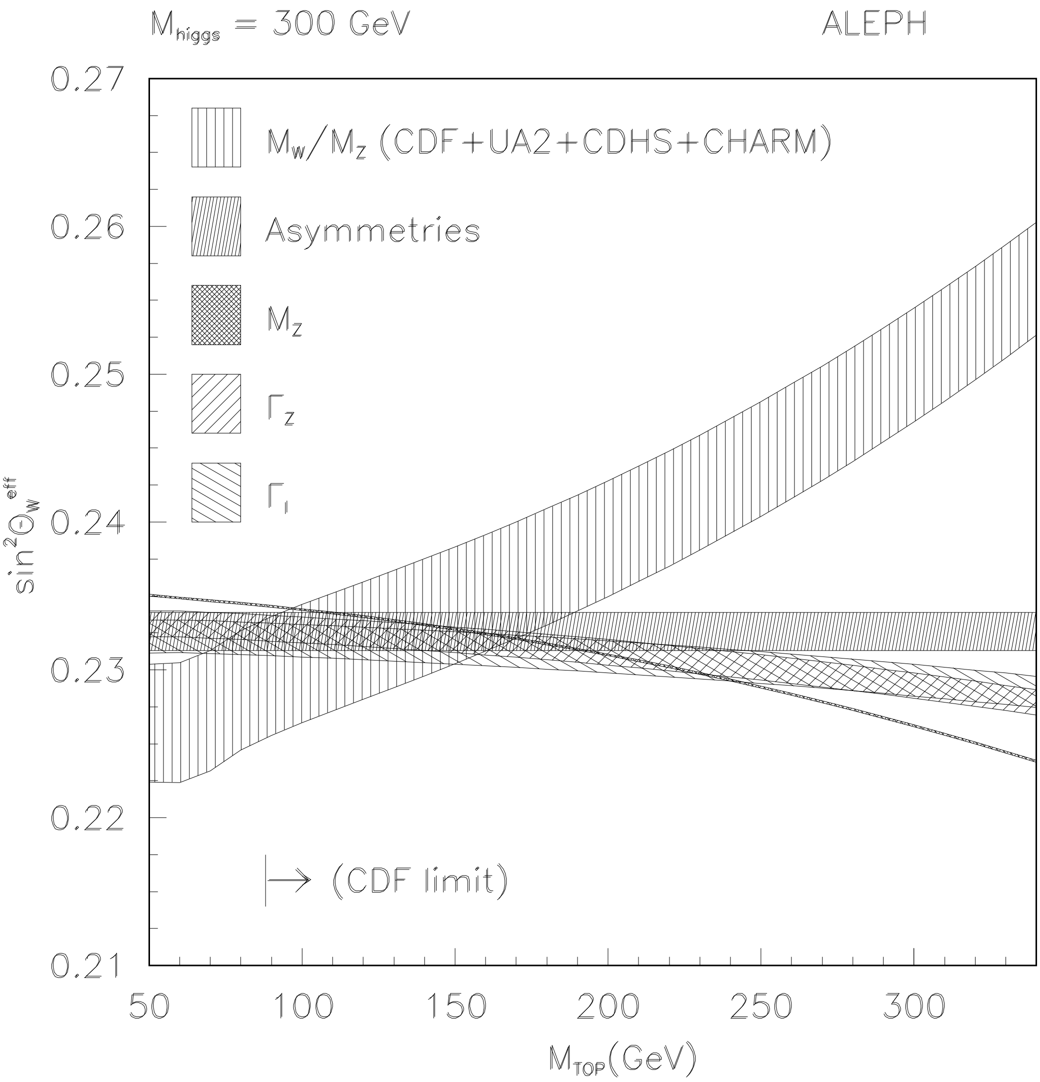

Figure 8: Constraints on $\sin^2\theta_{\mathrm{W}}^{eff}$ versus M_{top} from different measurements assuming $M_{\mathrm{Higgs}} = 300$ GeV.

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A Appendix

A.1 Correlation Matrix for 4-Parameter Lineshape Fit

	Γ_{Z}	σ^0_{had}	R_ℓ
M_{Z}	0.02	0.03	0.00
Γ_{Z}	-	-0.20	-0.01
σ^0_{had}		-	0.16

A.2 Correlation Matrix for 6 Parameter Lineshape Fit

	Γ_{Z}	σ^0_{had}	R_e	R_μ	R_τ
M_{Z}	0.02	0.03	0.00	0.00	0.00
Γ_{Z}	-	-0.20	-0.02	0.01	0.00
σ^0_{had}		-	0.10	0.10	0.09
R_e			-	0.07	0.06
R_μ				-	0.06

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